Experimental Characterization and Validation of Simultaneous Gust Alleviation and Energy Harvesting for Multifunctional Wing Spars

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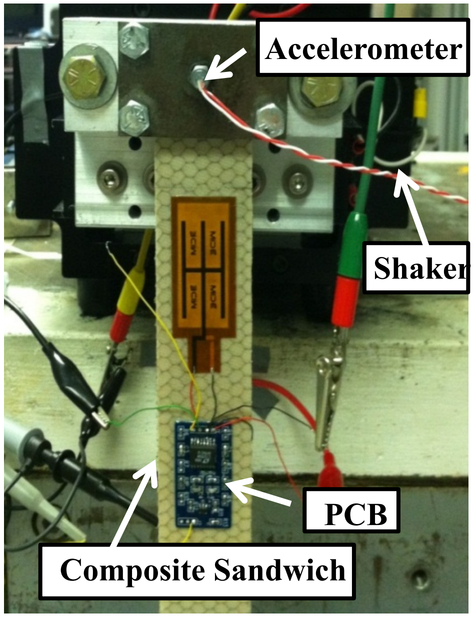

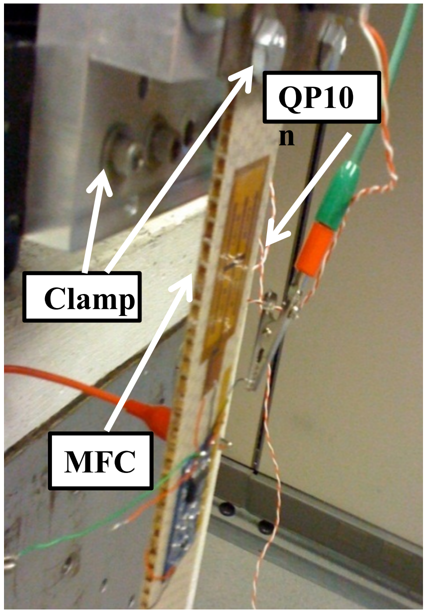

Research Issues:

1. Characterization of appropriate ambient energy
2. Characterization of sensing, harvesting, actuation, associated electronics
3. Validation of reduced energy control laws with limited energy
4. Validation of autonomous gust alleviation system

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Experimental Characterization of Transduction Abilities

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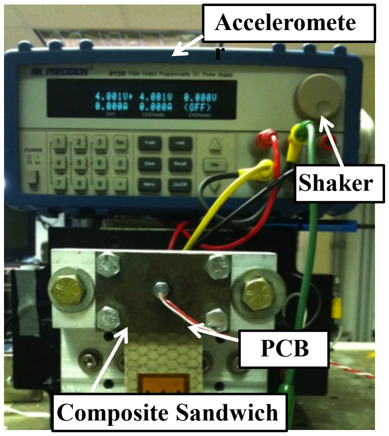
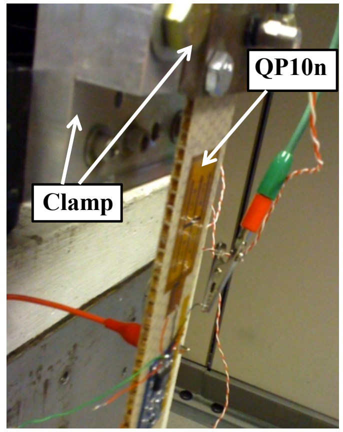
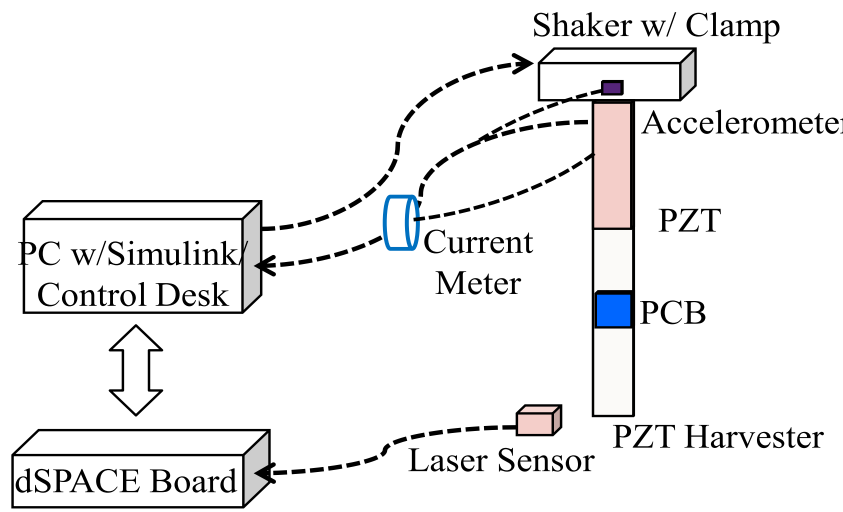
Experimental Setup for Transduction Characterization of QP and MFC

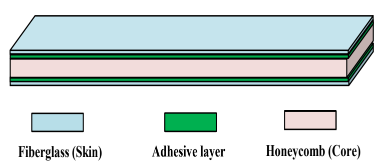


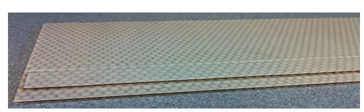


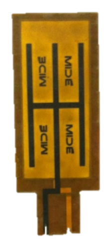


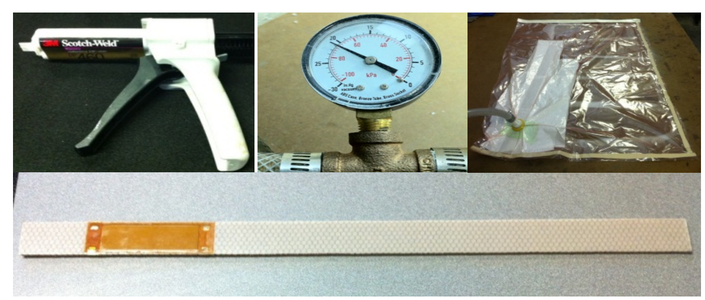
Which is the best transducer?
What is the coupling coefficient?
What is the internal capacitance?

Property/Component	QP10n	MFC8528P1	Composite Substrate
Overall Length	50.8 mm	112 mm	593.7mm
Overall Width	25.4 mm	40 mm	38mm
Overall Thickness	0.508 mm	0.18 mm	3.175mm
Overall Mass	2.835 gram	4.06 gram	13.97gram
Nominal Distance	34.5 mm	34.5 mm	N/A

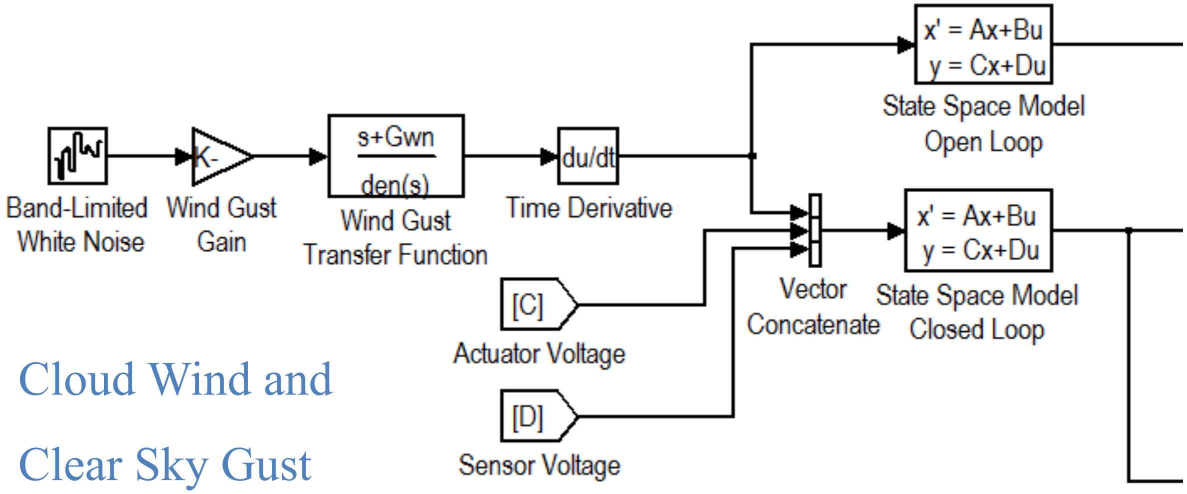








Simulations of Normal Vibration and Wind Gust



$$\Phi_v(\omega) = K_g^{\,2}\,|G_v(\omega)|^2\,\Phi_N(\omega)$$

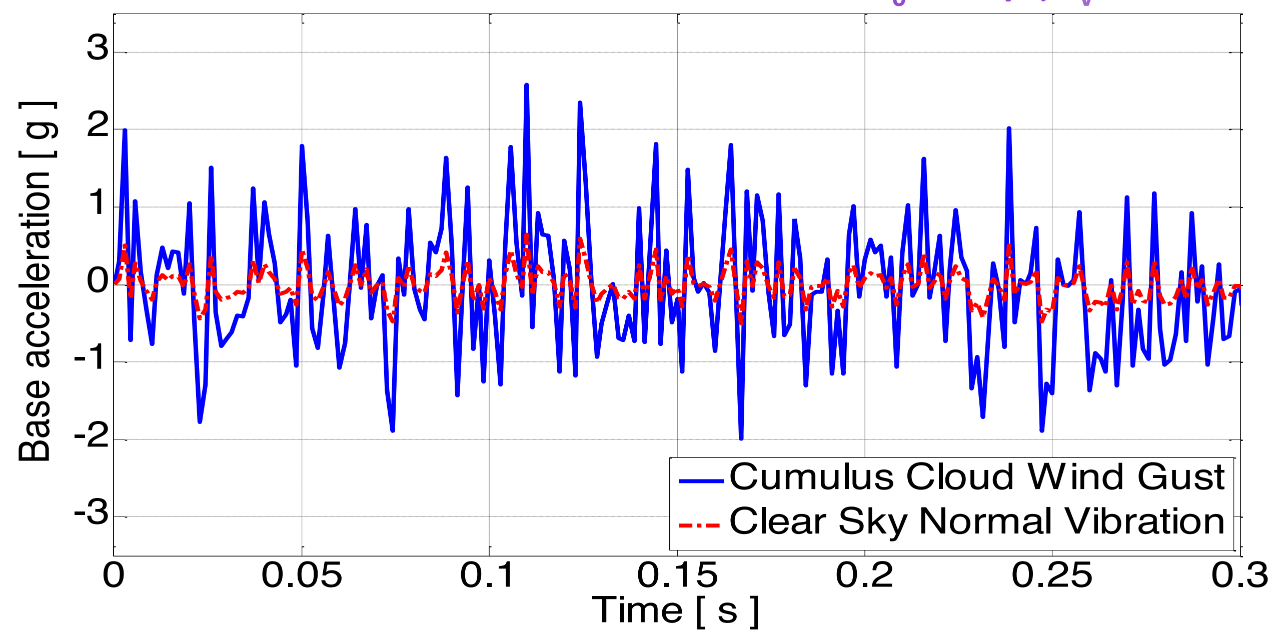
$$K_g = \sqrt{\frac{3\sigma_v^2 U_0}{\pi L_v}},\quad G_v(s) = \frac{s + \frac{U_0}{\sqrt{3}L_v}}{\left(s + \frac{U_0}{L_v}\right)^2}$$

$$U_0 = \sqrt{\frac{2W}{\rho_\infty S C_{Ltrim}}}$$

U_0=15m/s, L_v =350m

Cloud Wind and Clear Sky Gust Simulation Using Dryden PSD*

Harvested Energy from Normal Vibration (Red) to Control Wind Gust Disturbance (blue)



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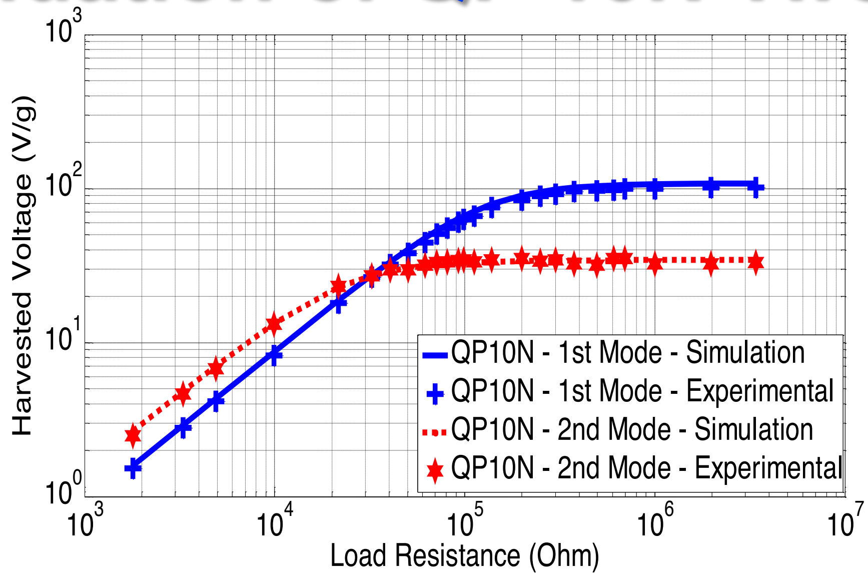
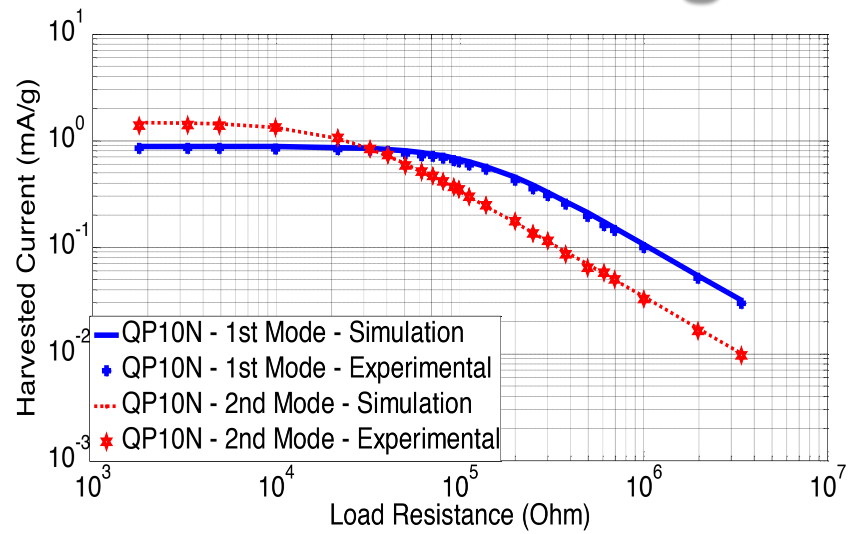
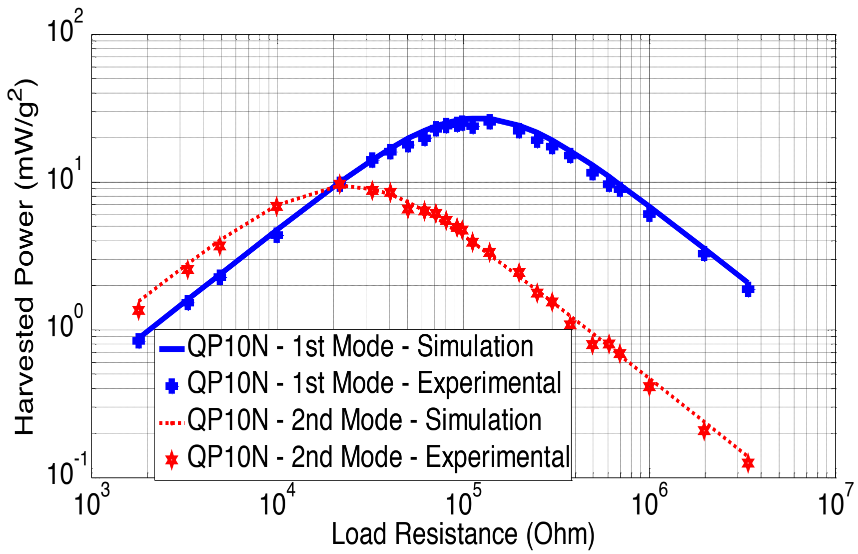
Ref: *McLean, D, 'Automatic Flight Control System' , Prentice Hall, 1990

Validation of QP 10N Two Mode Harvesting





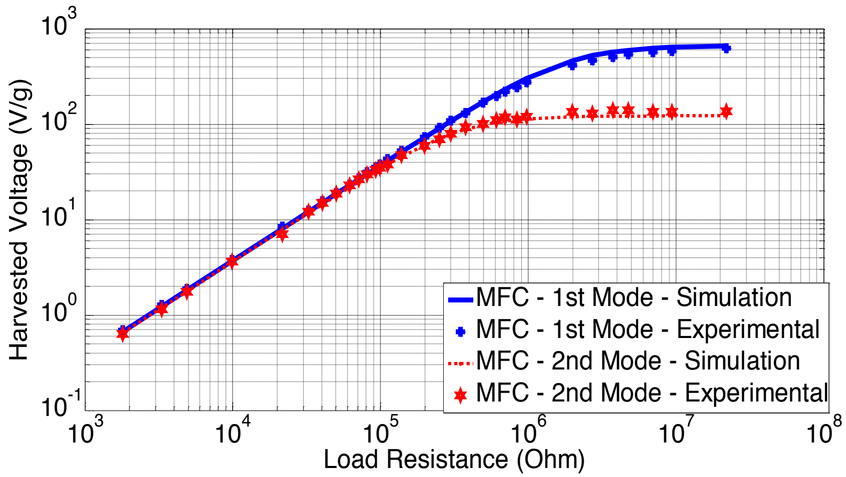


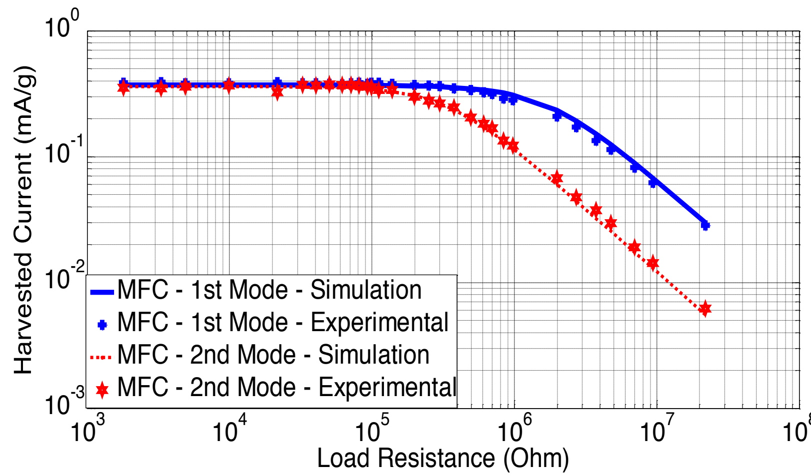
Peak Power Amplitude [QP]:

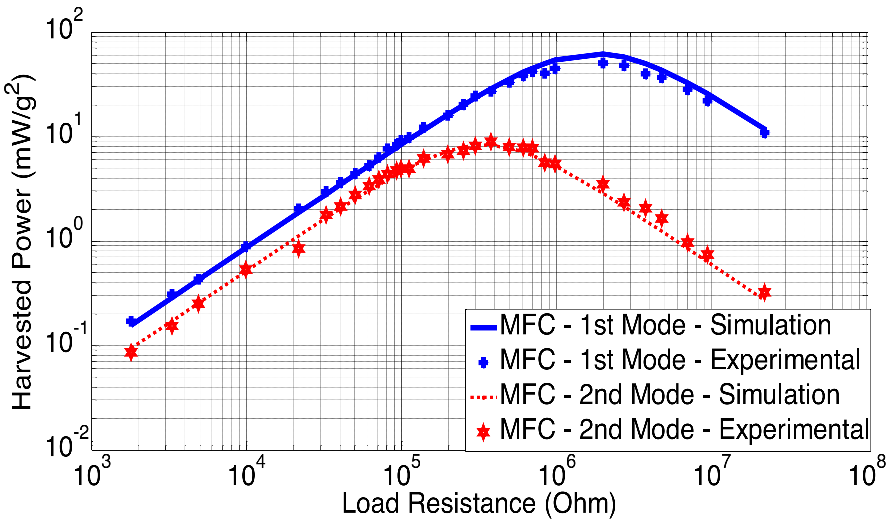
28.2mW/g^2 1st mode @ 112kΩ

9.8mW/g^2 2nd mode @ 20.2kΩ

Validation of MFC Two Mode Harvesting







Peak Power Amplitude [MFC]:

50.8 mW/g^2 1st mode @ 1.98 MΩ

9.8 mW/g^2 2nd mode @ 0.35 MΩ

Looks like MFC is better than QP except not if normalized by active volume of PZT

Experimental Results of Transduction Characterization

Hamilton Principle **Governing Equations**

$$\int_{t1}^{t2}(\delta T_e - \delta U + \delta E_{ie} + \delta E_{nc})dt = 0. \Rightarrow$$

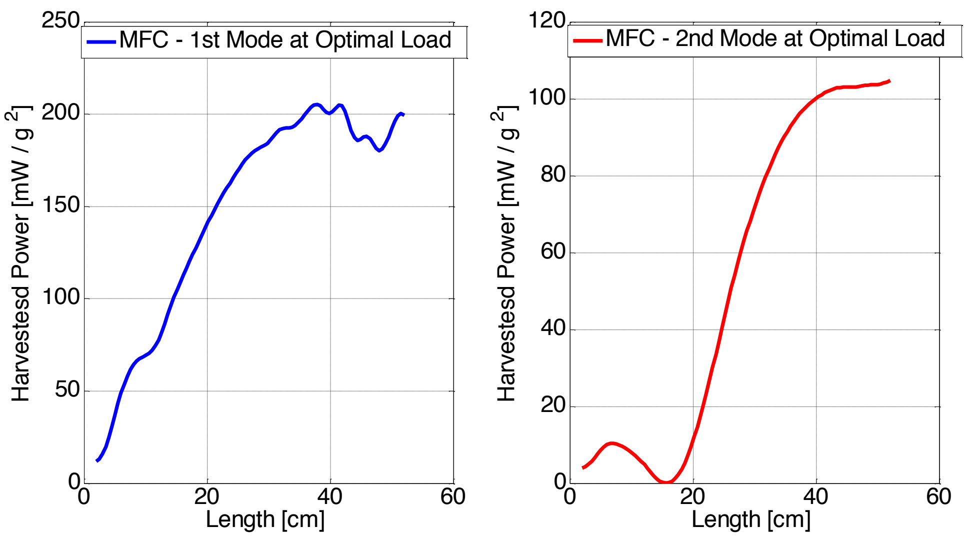
$$\mathbf{M}\ddot{\eta} + \mathbf{C}\dot{\eta} + \mathbf{K}\eta = \mathbf{f} + \theta^h V^h$$

$$C_p^h \dot{V}^h + i^h + \theta^h \dot{\eta}^h = 0$$

Property/Component	QP10n	MFC8528P1	Composite Substrate
Active Length	45mm	85mm	559.2mm
Active Width	20mm	28mm	38mm
Thickness	0.38mm	0.18mm	3.175mm
Mass	2.30gram	4.06gram	13.97gram
Young's Modulus	51GPa	42GPa	10.29GPa
Internal Capacitance	117nF	7.9nF	N/A
Piezoelectric Coefficient d_{33}	-190e-12	400e-9	N/A
Effective Distance from Clamp	38.4mm	30.5mm	N/A

Transducer data from experimental identification

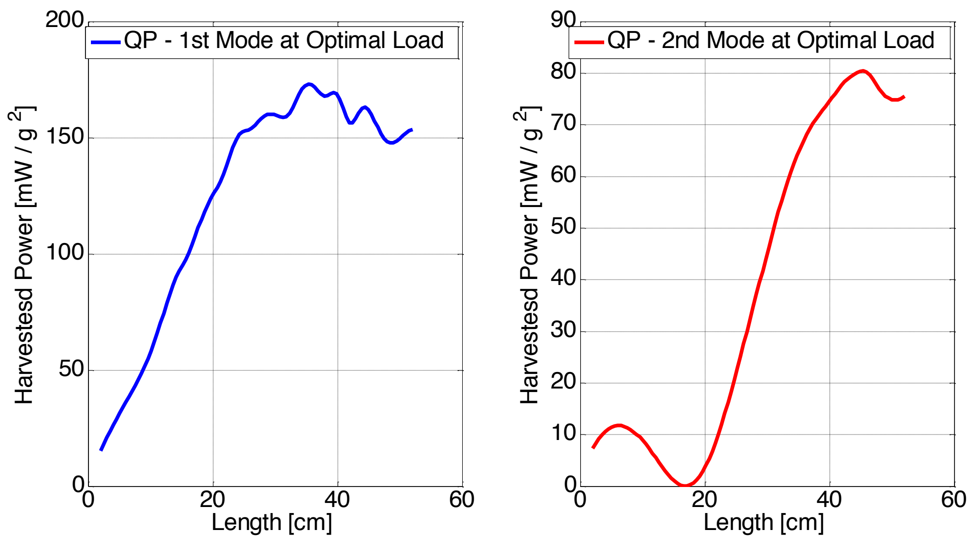
Optimal length for Harvesting Effectiveness



Output Power of MFC versus Active Length at Mode 1 of 29 Hz and Mode 2 of 107Hz.

Stewart, Weaver and Cain (2012) reported theoretically and experimentally that harvested energy in the fundamental mode maximized with an active length (electrode coverage) of exactly 2/3 of the beam length from the root.

Expanded result to the 2nd mode



Output Power of QP versus Active Length at Mode 1 of 29 Hz and Mode 2 of 107Hz.

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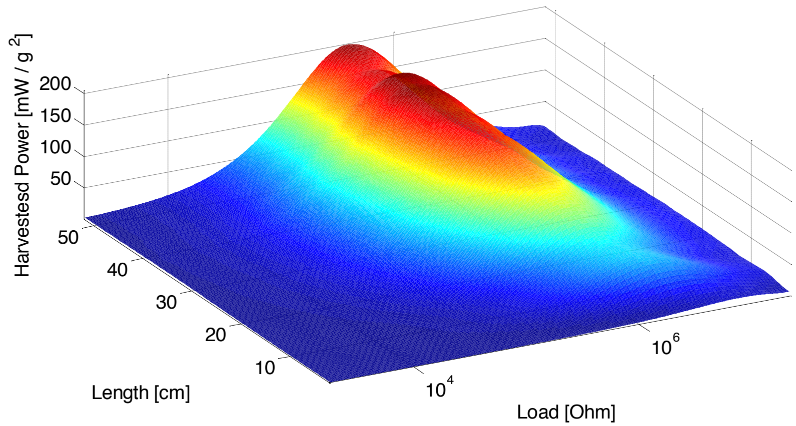
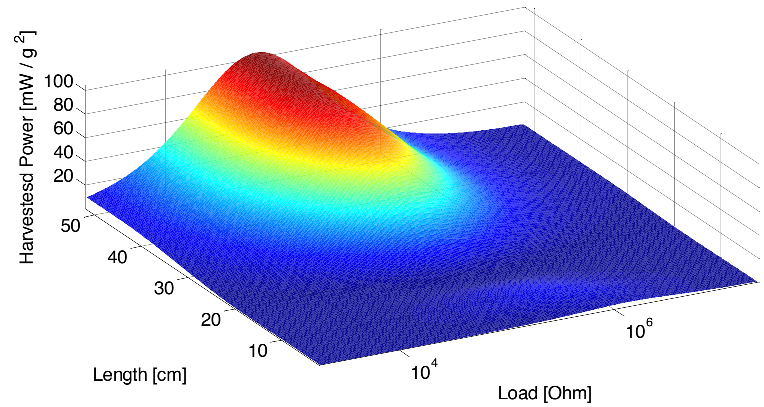
Design Consideration on Harvesting Effectiveness



Power vs. Optimal Load Vs. Length
MFC 8528P1 @ Mode 1 @ 29Hz

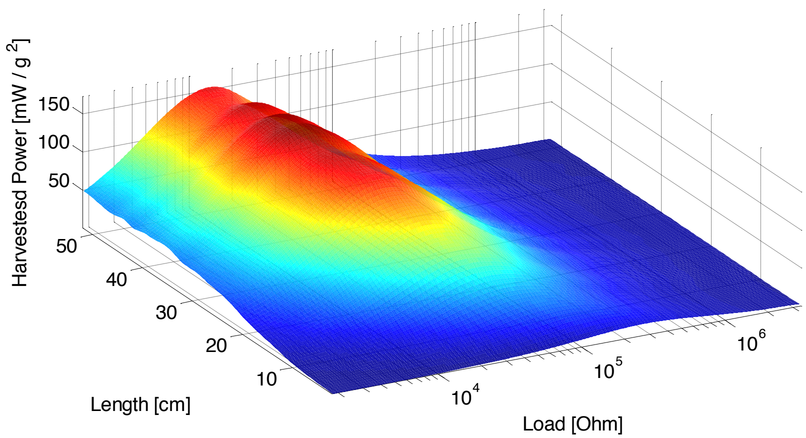


Power vs. Optimal Load Vs. Length
MFC 8528P1 @Mode2 @ 107Hz

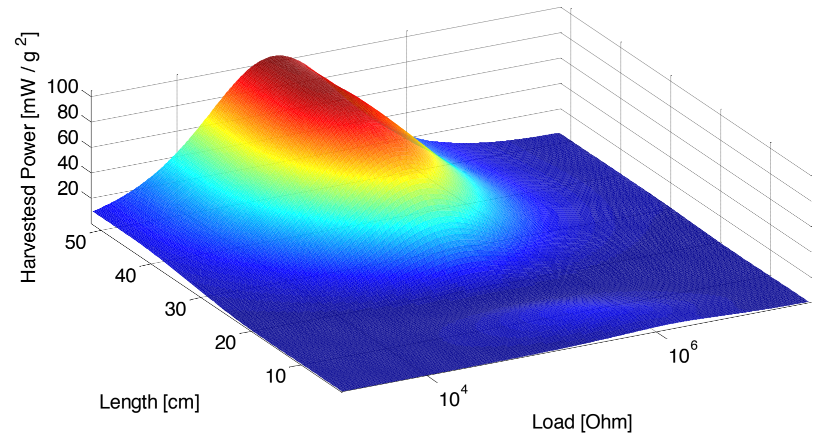
Devices	MFC 8528P1
active length x width	85mm x 28 mm
thickness	0.18mm
mass	4.06g
elastic modulus	42GPa
operating mode	{3-3}
capacitance	5.7nF
pzt constant d31/d33	400pC/N
coupling coefficient J_p	8.9e-5

Simulations to compare power with active sensing length, load resistance for an MFC Sensor

Design Consideration on Harvesting Effectiveness



Power vs. Optimal Load Vs. Length
QP10n @ Mode 1 @ 29Hz



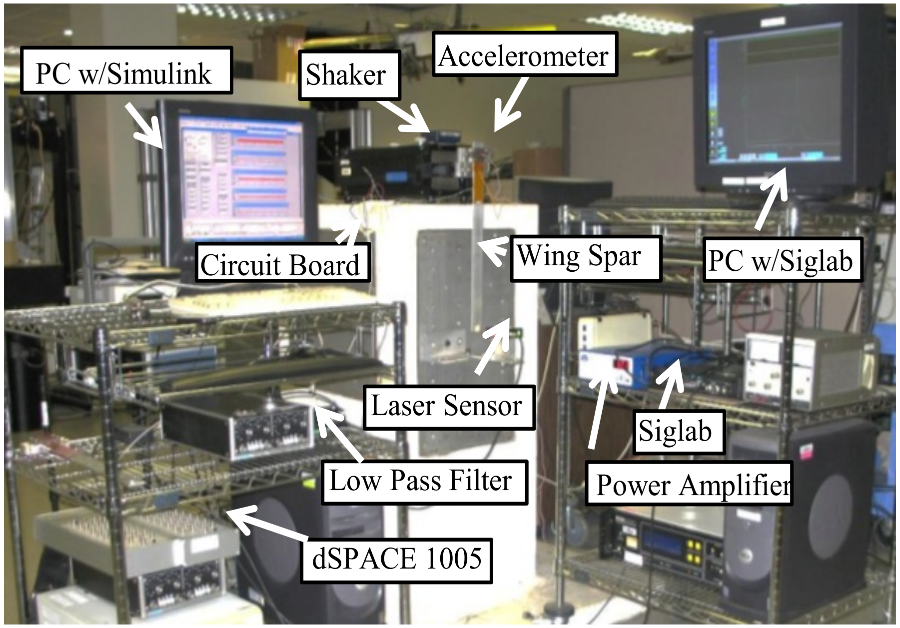
Power vs. Optimal Load Vs. Length
QP10n @ Mode 1 @ 29Hz

Devices	QP10n
active length x width	45mm x 25.4mm
thickness	0.38mm
mass	2.3g
elastic modulus	51Gpa
operating mode	{3-1}
capacitance	117nF
pzt constant d31/d33	-190pC/N
coupling coefficient J_p	-4.4e-4

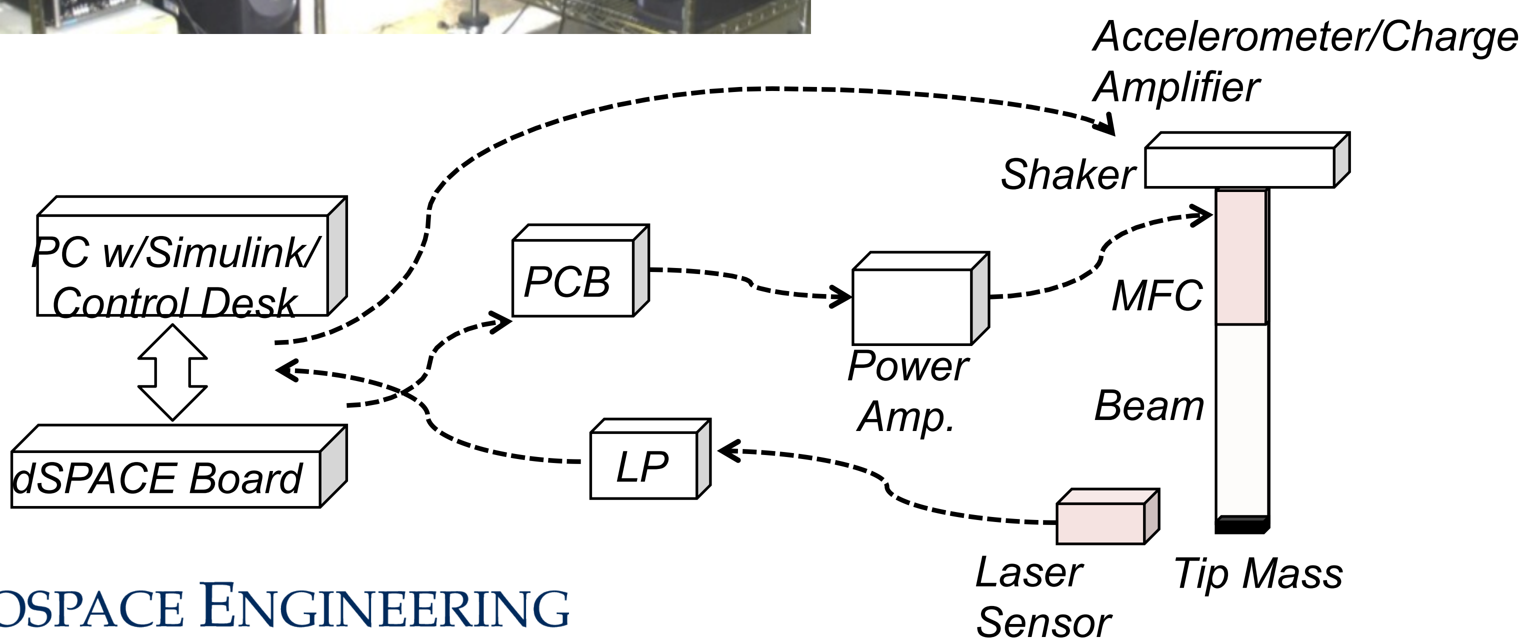
Simulations to compare power with active sensing length, load resistance for an QP Sensor

Experimental Validation of Reduced Energy Control

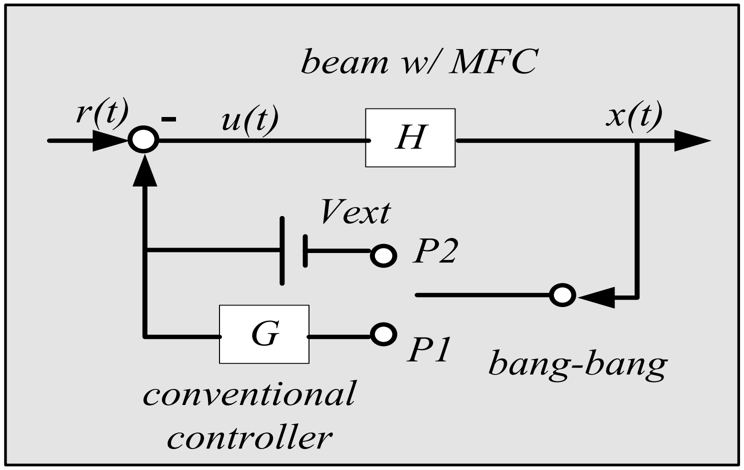
Experimental Setup for Reduced Energy Control via MFC



Property/Component	MFC	Al Substrate
Clamped Length	112mm	450mm
Width	40mm	28mm
Thickness	0.18mm	3.05mm
Mass	4.06g	139.4g



Reduced Energy Control Laws



Case I: $u(t) > 0$

If $u(t) < V_{ext}$, connect to P1, then $u=u(t)$;

if $u(t) \geq V_{ext}$, connect to P2, then $u=V_{ext}$;

Case II: $u(t) < 0$

if $u(t) \leq V_{ext}$, connect to P2, then $u= V_{ext}$;

if $u(t) > V_{ext}$, connect to P1, then $u= u(t)$.

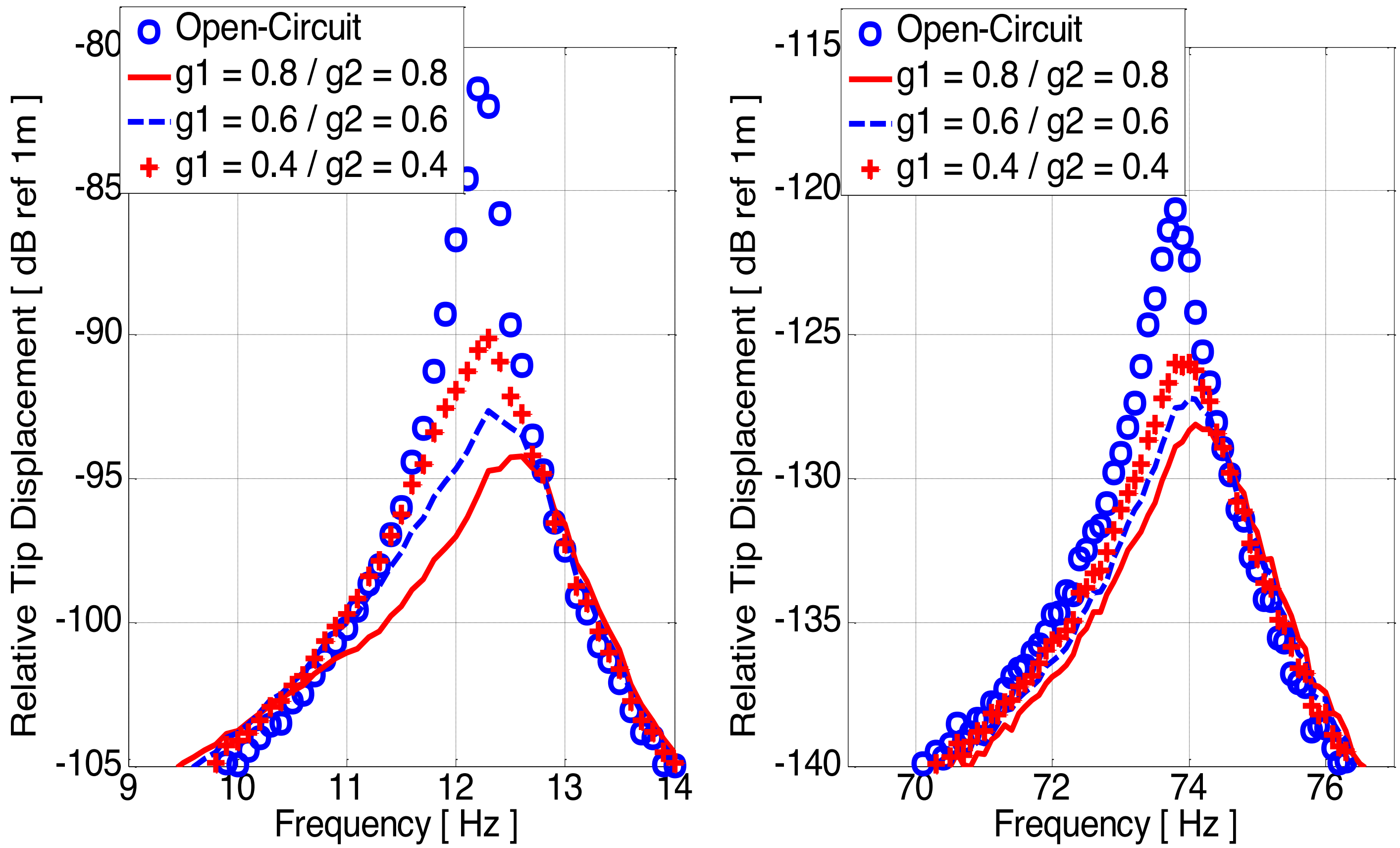
Design Methodology:

Cut off higher levels of actuation voltage by saturating control sources;

Reduce the average actuation power input flowing into piezoceramic actuator until control performance is reached

Ref: *Wang Y., Inman D.J. (2011) “Comparison of Control Laws for Vibration Suppression Based on Energy Consumption ," JIMSS, 22(8) pp.795-809

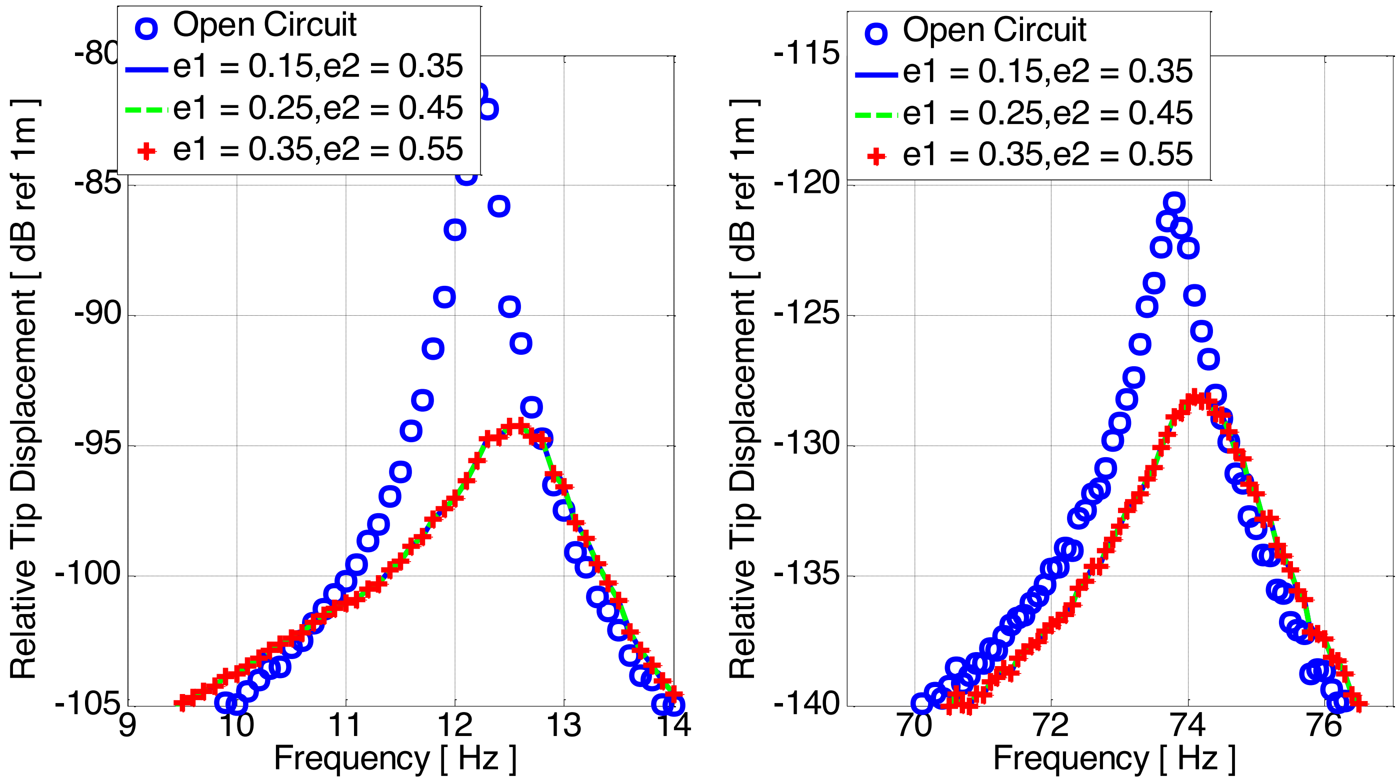
Experimental Characterization of Control Performance



damping ratio of mode 1: ζ_1= 0.15 and mode 2: ζ_2 = 0.35

1st Mode Control Gain	0.8	0.6	0.4
2nd Mode Control Gain	0.8	0.6	0.4
1st Mode Reduction	13dB	11dB	9dB
2nd Mode Reduction	8dB	7dB	6dB

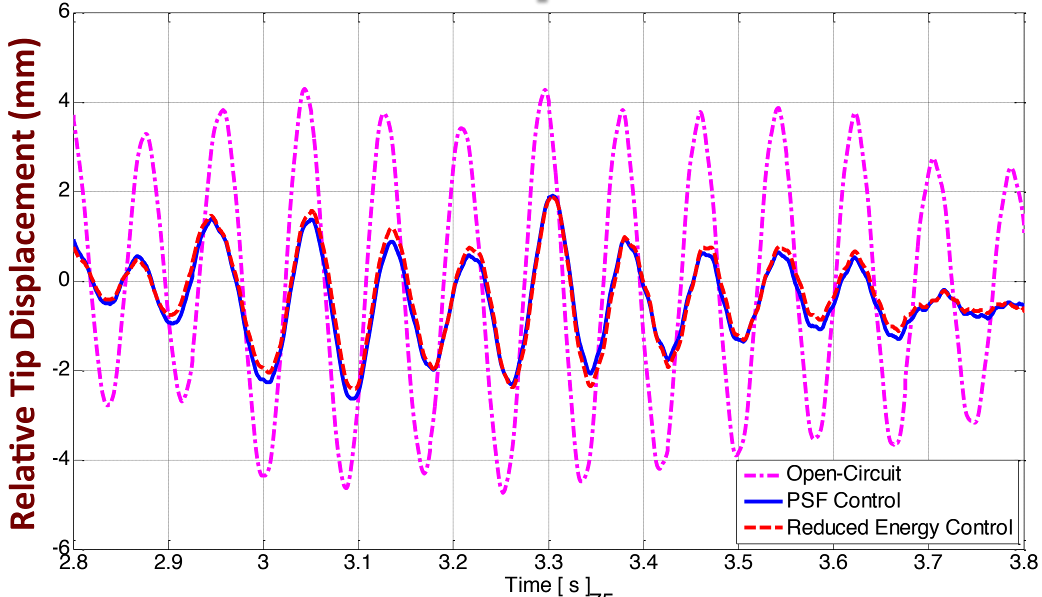
Experimental Characterization of Control Performance



damping ratio of mode 1: g_1= 0.6 and mode 2: g_2 = 0.6

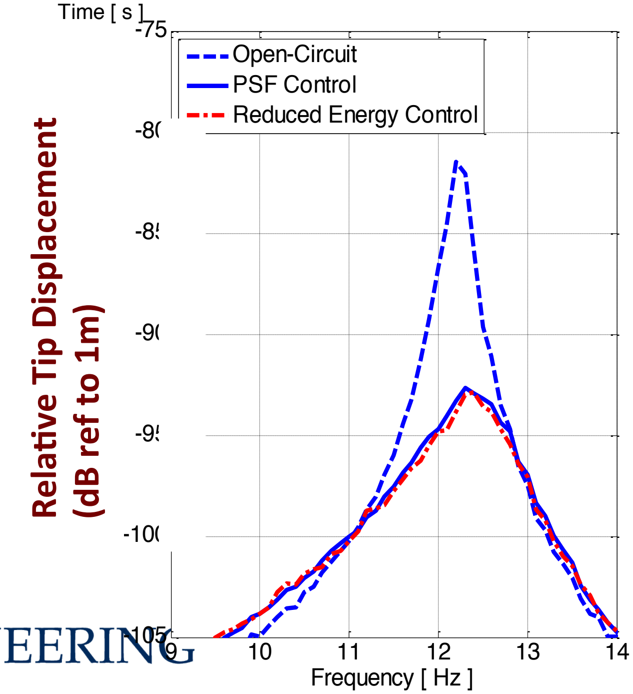
Shows that velocity gain in controller does not effect performance

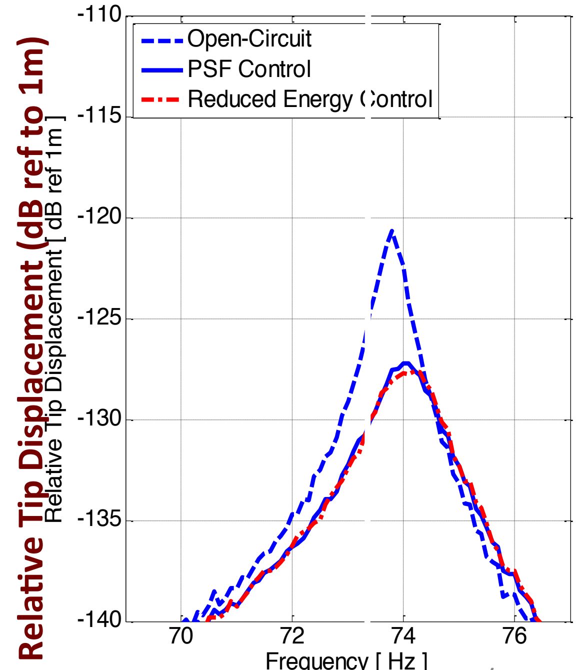
Experimental Comparison of Control Performance



RMS value : 3 mm to 1.2 mm

14 dB reduction for 1st Mode
12 dB reduction for 2nd Mode





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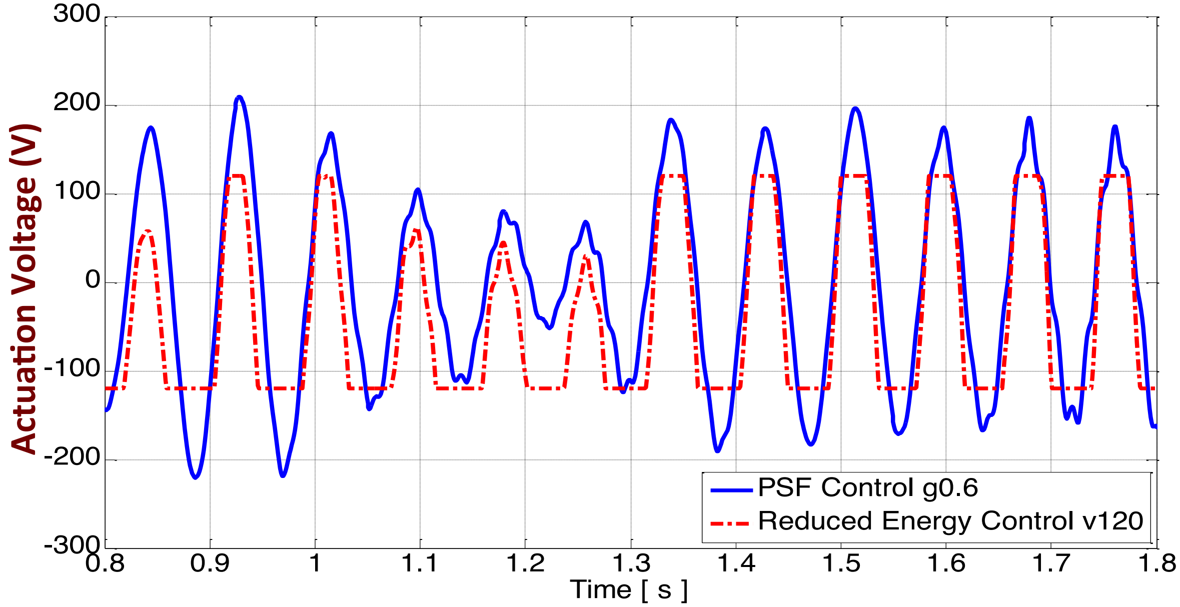
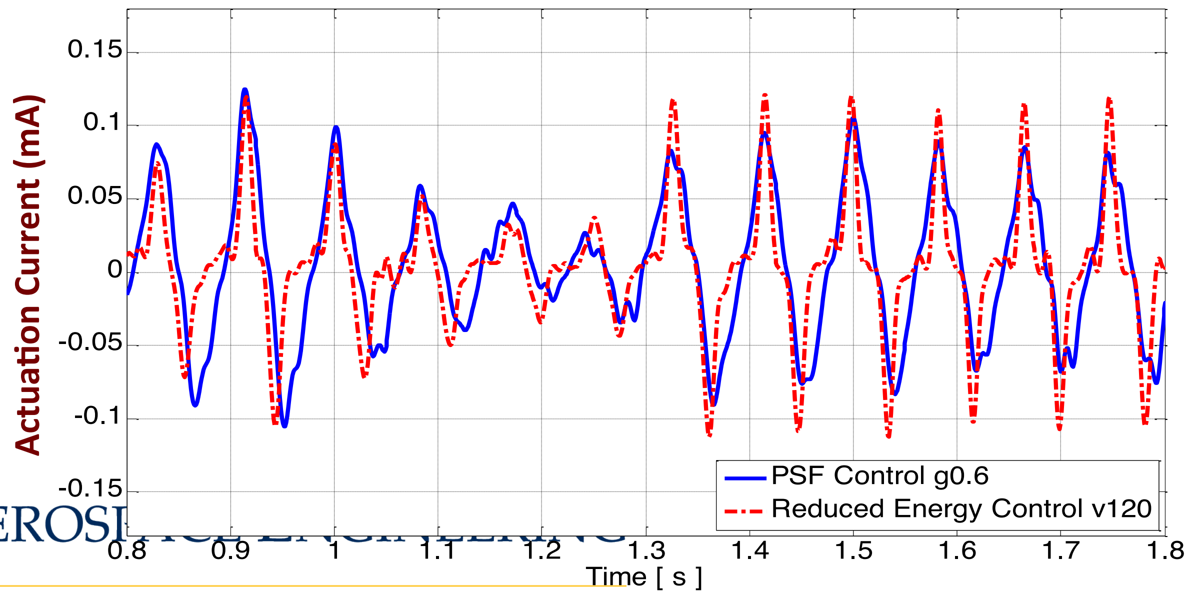
Experimental Comparison: Reduced Energy Control vs. PSF

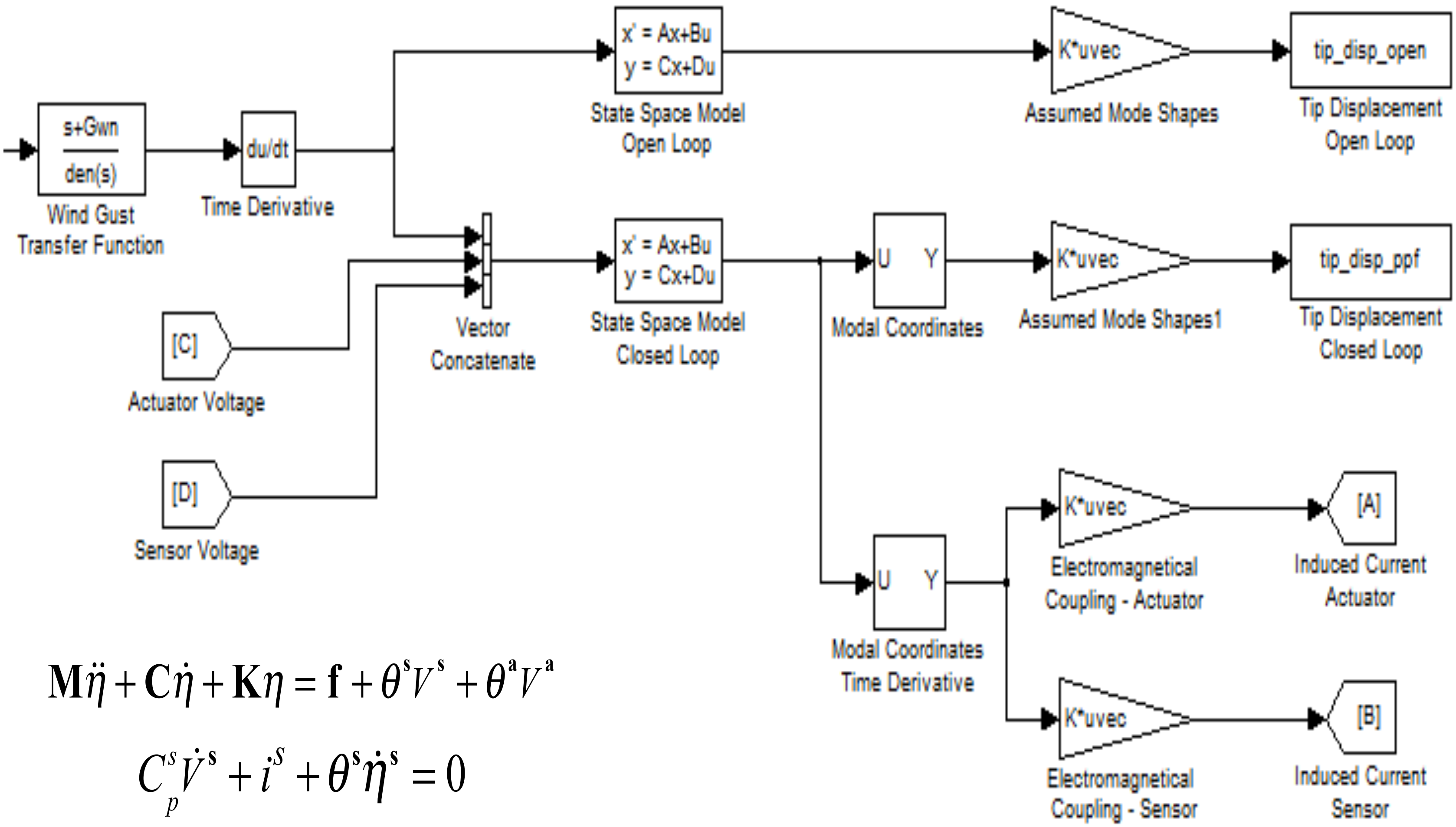


REC cut off higher levels of actuation voltage



current from REC has sharp change while the saturation occurs, due to the sharp switching in voltage, and it drops down rapidly after saturation finishes

Schematic Autonomous Gust Alleviation System



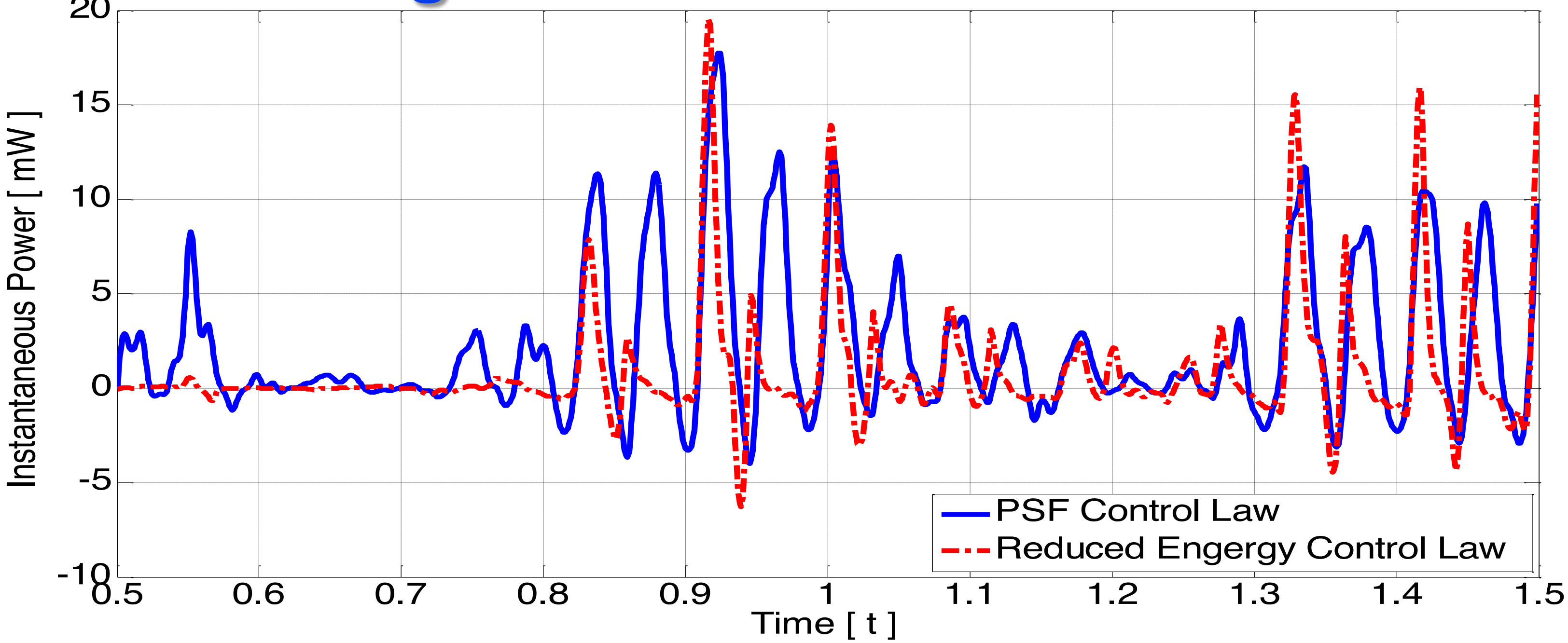
$$\mathbf{M}\ddot{\eta} + \mathbf{C}\dot{\eta} + \mathbf{K}\eta = \mathbf{f} + \theta^{s}V^{s} + \theta^{a}V^{a}$$

$$C_p^{s}\dot{V}^{s} + i^{S} + \theta^{s}\dot{\eta}^{s} = 0$$

$$C_p^{a}\dot{V}^{a} + i^{a} + \theta^{a}\dot{\eta}^{a} = 0$$

Ref: Wang, Y., Inman, D. J. (2012) Journal of Composite Materials

Experimental Comparison of Actuation Power to reach 5% settling time



Element	PSF	REC	Ratio of Reduction
Voltage RMS (V)	100	82.3	18 %
Current RMS (mA)	0.065	0.053	18 %
Required Energy E_{tr} (mJ)	6.6	1.6	76 %
Average Power P_{st} (mW)	1.2	1.0	17 %

Experimental Validation on Multifunctional Composite Wing Spar

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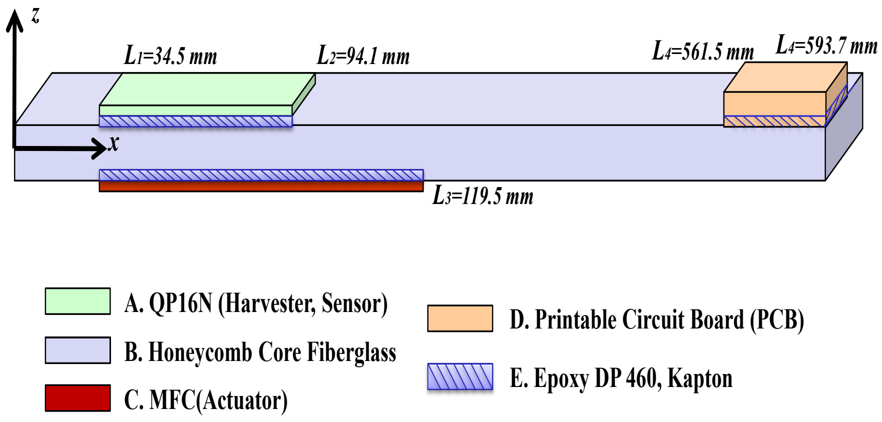
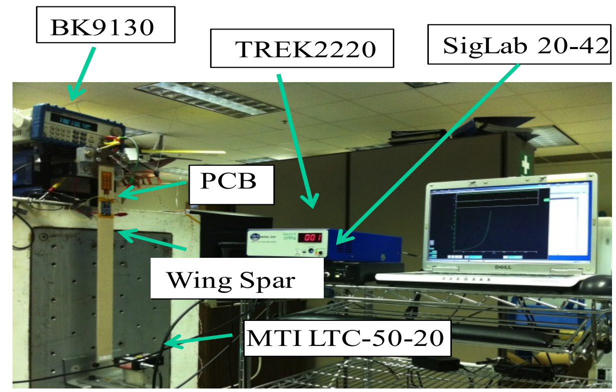
Experimental Setup for Autonomous Gust Alleviation





Property/Component	QP10n	MFC8528P1	Composite Substrate
Active Length	45mm	85mm	559.2mm
Active Width	20mm	28mm	38mm
Thickness	0.38mm	0.18mm	3.175
Mass	2.30gram	4.06gram	13.97gram
Young's Modulus	51GPa	42GPa	10.29GPa
Internal Capacitance	117nF	7.9nF	N/A
Piezoelectric Coefficient d_{33}	-190e-12	400e-9	N/A
Effective Distance from Clamp	38.4mm	30.5mm	N/A

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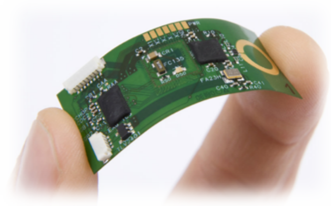
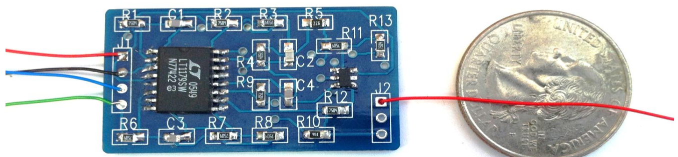
Equivalent Circuit of a Reduced Energy Controller

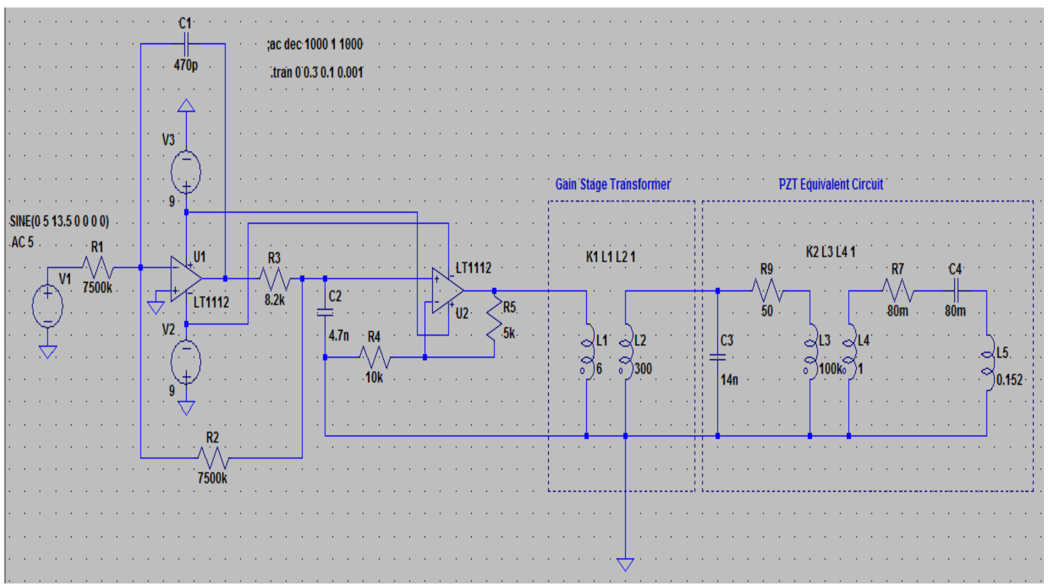


$$\frac{v_o}{v_i} = k\frac{\omega_f^2}{s^2 + 2\zeta_f\omega_f s + \omega_f^2}.$$



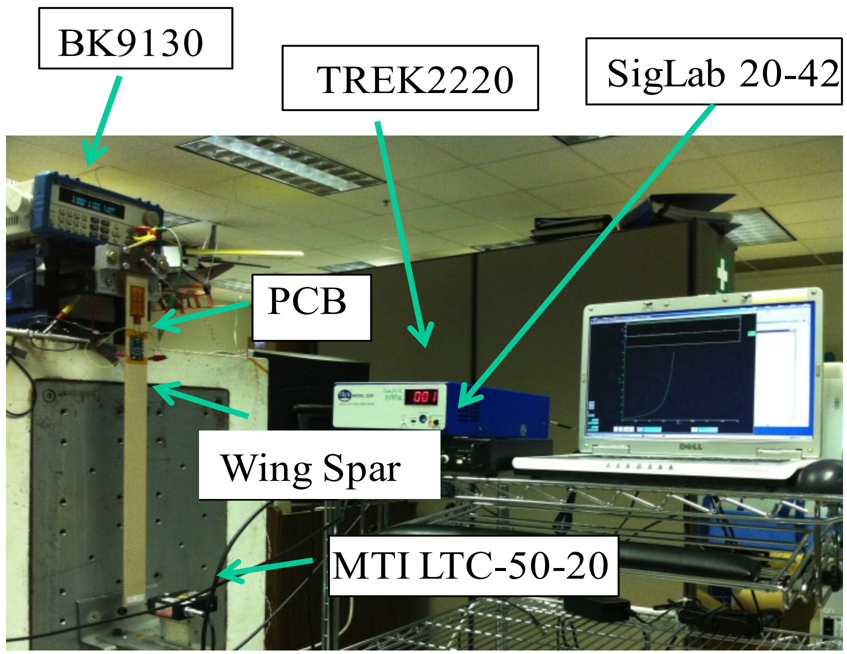
1st order PSF control

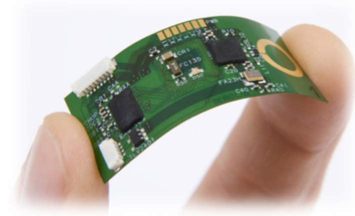
$$k = \frac{R_2}{R_1}\left(1 + \frac{R_5}{R_4}\right), \omega_f^2 = \frac{1}{C_1C_2R_2R_3}, \zeta_f = \frac{C_1(R_2 + R_3)\omega_f}{2}.$$

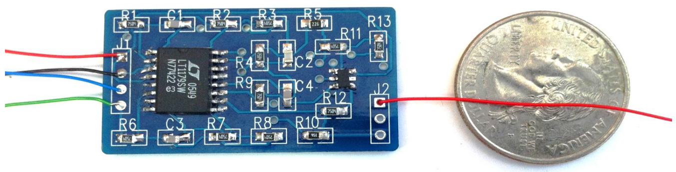


Component Symbol	Nominal Values	Component Purpose
C1	150pF	C1_1st Mode
C2	5600pF	C2_1st Mode
C3	150pF	C1_2nd Mode
C4	500pF	C2_2nd Mode
R1	7.5MΩ	R1_1st Mode
R2	7.5MΩ	R2_1st Mode
R3	10MΩ	R3_1st Mode
R4	7.5MΩ	R4_1st Mode
R5	22.5MΩ	R5_1st Mode
R6	7.5MΩ	R1_2nd Mode
R7	7.5MΩ	R2_2nd Mode
R8	7.5MΩ	R3_2nd Mode
R9	7.5MΩ	R4_2nd Mode
R10	15MΩ	R5_2nd Mode
R11	7.5MΩ	Summing R1
R12	7.5MΩ	Summing R2
R13	7.5MΩ	Summing R3
J1		Inputs
J2		Outputs
U1		LT1179SW
U2		LT1782IS5

Experimental Characterization of Component Properties

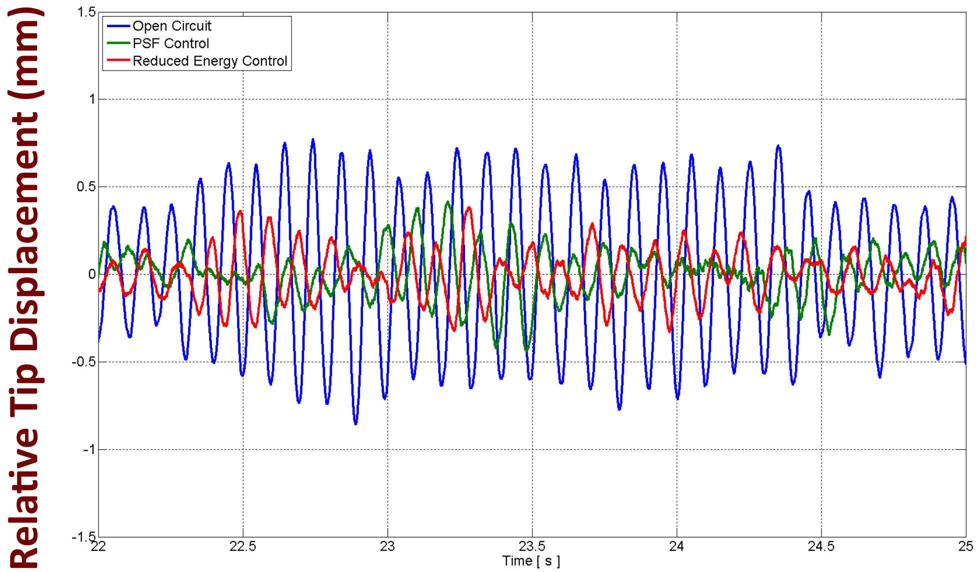


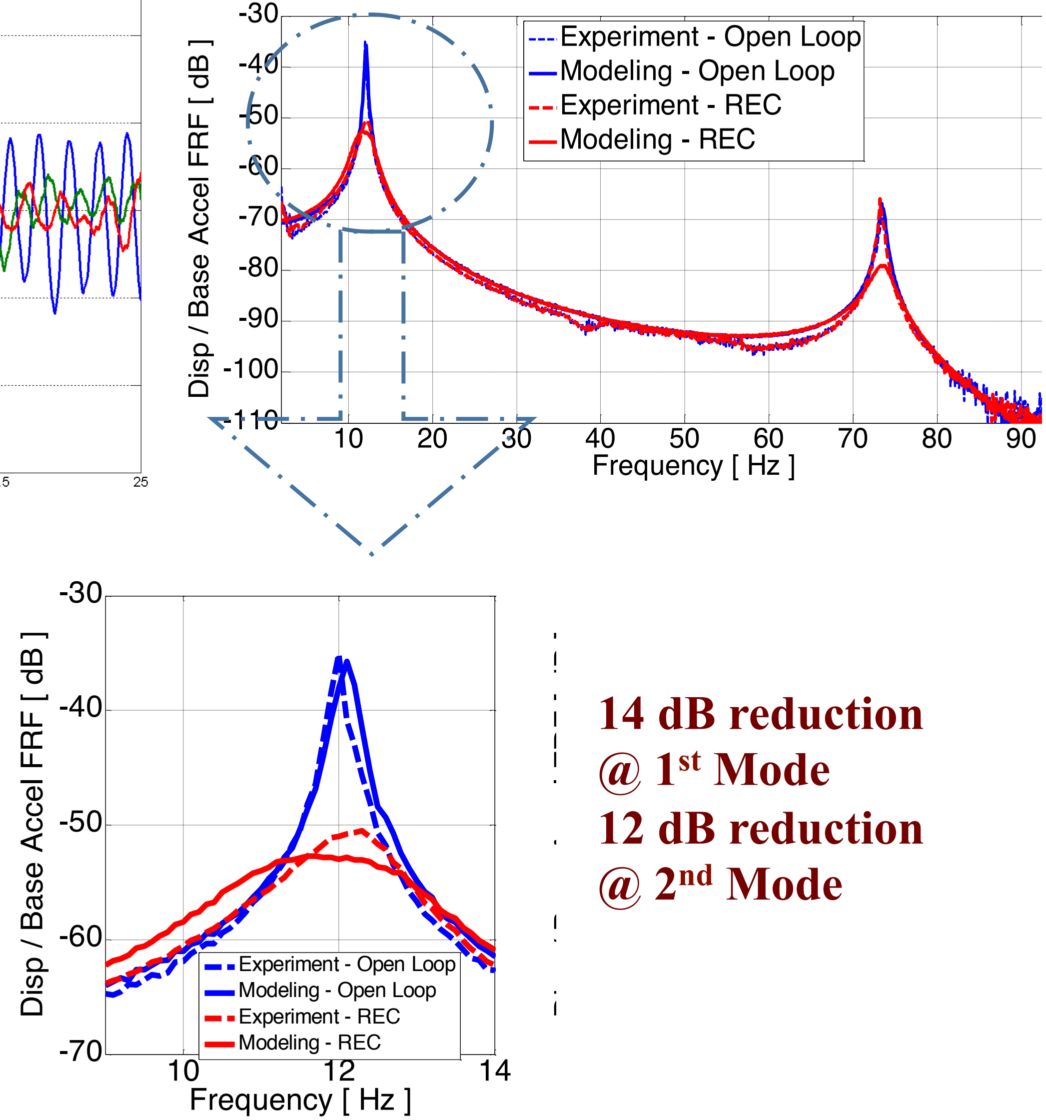




Property/Component	PCB
Length	40 mm
Width	10 mm
Thickness	1.016 mm
Distance from clamp to start of PCB	114 mm
Mass	2.625gram
Young's Modulus	30 GPa

Experimental Measurement of Gust Alleviation





0.45 mm (RMS)
to 0.09 mm (RMS)

14 dB reduction
@ 1st Mode
12 dB reduction
@ 2nd Mode

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Does it work?

- For any wind gust duration $t_g >$ settling time t_s>0.8s, the total control energy satisfy:

$$E_{tot} = E_{tr} + P_{st} * (t_g - t_s).$$

- Then the total control energy required by PSF and REC becomes:

$$E_{tot}^{PSF} = 6.6 + 1.2 * (t_g - 0.8).$$

$$E_{tot}^{REC} = 1.6 + 1.0 * (t_g - 0.8).$$

- For average harvested power P^{harv}, the required harvesting time t_h to control a wind gust of duration t_g yields:

$$t_h = \frac{E_{tot}}{P^{harv}}.$$

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Concluding Remarks

Summary Comments

1) Established ambient vibration levels in time histories

2) Fabricated a multifunctional wing spar

3) Derived a predictive model for energy conversion from embedded PZT and MFC including associated electronics

4) Experimentally characterized reduced energy control law based on limited energy constraints

4) Experimentally validated simultaneous energy harvesting and vibration control

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